A STUDY OF UNPILOTED IGNITION OF PLANAR SURFACE PONDEROSA PINE

by

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THESIS

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ABSTRACT

The unpiloted ignition of wood caused by thermal radiation varies widely when only small areas of the test panel are irradiated. In order to make a comparison of the effect of a given variable, which in this case was water content, a statistical method was devised which yielded a 50% probability of ignition point as a standard of comparison. The results of the testing were predictable at higher water contents in which the requisite heat flux to produce ignition was an increasing function of increasing water content. At extremely low water content an unexpected increase in the requisite heat flux required for ignition was observed. While several explanations are possible to account for the observed anomaly, selection of any one exclusive explanation was not made due to the lack of sufficient data.

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I. INTRODUCTION

Ignition of materials by thermal radiation is generally divided into two classifications:

1) Unpiloted ignition
2) Piloted ignition

Unpiloted ignition results when a flame is produced by thermal radiation alone igniting the irradiated material. No added assistance such as an electric spark, pilot flame, or flame wall is used to ignite the outgassing products from the target material.

Piloted ignition results when a pilot flame or supplementary ignition device is employed to ignite the outgassing products produced by thermal irradiation of the target material.

It was decided to conduct unpiloted ignition studies of vertical surface ponderosa pine in order to develop testing methods for evaluating variable factors that had an effect on ignition, particularly in materials of non-uniform composition. Factors of equipment cost, simplicity of method, and most important of all, reproducibility of results were taken into account in devising the testing methods described herein.

Reproducibility of results is a major problem in the field of combustion studies. Lack of reproducible results appear to derive from the following causes:

1) The materials under study are often of a non-uniform nature or composition.
2) Significant variables such as water content are often neglected.

3) Experimental equipment, methods, procedures, and interpretation of results vary widely with different researchers.

Realizing these three problems, and in order to develop an acceptable testing procedure, ponderosa pine, a material of non-uniform composition, was chosen to be the test material. The variable factor chosen for study was water content. The choice of experimental apparatus, selection of testing procedures, and methods of data interpretation were made in such a way as to maximize reproducibility without unduly sacrificing simplicity of equipment and experimental procedures.

In addition to illustrating the correlation between requisite heat flux intensity for unpiloted ignition and water content of ponderosa pine, it is hoped that the methods demonstrated will be of further use in comparing the effect of a given variable over its range in either a single material or several related materials as that variable relates to unpiloted ignition.

II. APPARATUS

A. HEAT SOURCE

For the complete range of experiments performed a tungsten filament iodine vapor-filled quartz bulb radiant heat projector was used.[1] By trial and error testing, a standoff distance of 6.7 ($\pm$ 0.1) cm. as measured from the horizontal edges of the projector assembly to the vertically positioned target surface was established and used as the standard standoff distance for all tests conducted. At this standard standoff distance a circular target area was produced of approximately 6-8 cm^2 at the time of unpiloted ignition which varied negligibly in size over the range of heat flux intensities employed.

The output of the heat source was controlled by the use of a calibrated adjustable autotransformer of 10 A current capacity. The voltage input to the heat source was the output of the autotransformer.

B. HEAT SOURCE CALIBRATION

The standard equation for determining heat flux upon a thin surface calorimeter of known mass, area and heat capacity is

$$F = \frac{M\ Cp}{A}\left(\frac{\Delta T}{\Delta t}\right) \tag{1}$$

wherein,

F = heat flux (cal/cm^2-s)
M = calorimeter mass (g)

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[1]Specifically used was the Model 3151-2 600W High Intensity Radiant Heat Projector manufactured by Cole-Parmer Instrument Company.

Cp = specific heat (cal/g-^oC)
A = calorimeter area (cm^2)
T = temperature interval (^oC)
t = time interval (s)

For the purposes of this calibration, the following calorimeter parameters remained constant:

M = .453g
Cp = .130 cal/g-^oC
A = 3.88 cm^2

These parameters yielded a calorimeter constant ($M \cdot Cp/A$) of 0.0182 cal/^{o}C-cm^2, which was applied to the individual temperature-time response curves of the calorimeter corresponding to various voltage inputs to the heat source.

The calorimeter employed for this calibration was a thin nickel alloy disc blackened with lampblack from burning toluene prior to each calibration run. The disc size enabled it to fit within the target area of the heat source at the standard standoff distance.

The temperature response of the calorimeter was measured by a pair of standard chromel-alumel thermocouple wires spot welded to the back of the disc. The thermocouple output was recorded on a millivoltage versus time in seconds scale using a calibrated X-Y recorder. The plotted output over the linear portion of the calorimeter response curves corresponding to various heat source input voltages was converted into a $\Delta T/\Delta t$ parameter for substitution into the heat flux equation (1)[1].

Table I shows the resultant heat flux values and the temperature-time parameters from which they were obtained for each corresponding voltage input to the heat source.

TABLE I

CALIBRATION VALUES

Input (volts)	$\Delta T/\Delta t$ ($^oC/s$	Flux (Cal/cm^2-s)
40	55.8	0.85
45	57.9	0.88
50	62.1	0.94
55	67.0	1.02
60	76.4	1.16
65	83.3	1.26
70	97.3	1.47
75	109	1.66
80	121	1.84
85	125	1.90
90	137	2.08
95	151	2.30
100	159	2.42

In order to transform the data points in the above table into a smooth calibration curve, the apparent linearity of the points above 50 V was noted. Using a small computing calculator[2], and an existing two variable linear regression analysis program within the machine's existing repetoire[3], the resulting equation

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[2]Wang Calculator, Model 370, manufactured by Wang Laboratories, Incorporated, Tewksburg, Massachusetts.

[3]Wang 300 Series Program Library, Volume 4, pp. 141 - 145, Wang Laboratories, Incorporated, 1968.

for heat flux (F) in terms of input voltage (V) was obtained:

$$F = .03166V - .7417 \tag{2}$$

Equation 2 was then plotted for the 50-100 V range with the values below 50 V empirically fitted to the balance of the curve. Figure 1 is the resulting calibration curve.

C. WATER CONTENT DETERMINATION

The water content of a given test specimen of wood may be determined by using procedures and apparatus suggested by the American Society for Testing Materials in ASTM Standard Test D 95-40 (b)[4] with the apparatus shown in Figure 2. When wood was used as tested material, the following modifications were found to be appropriate:

1) A 1000 ml distillation flask was used in place of the recommended 500 ml flask due to the bulkiness of the crushed wood sample.

2) The volume of distillation solvent was increased to approximately 450-500 ml, again due to sample bulk.

3) Toluene, due to its low and constant boiling point,[5] was used in preference to petroleum naphtha in order to prevent any wood pyrolysis with attendant exaggerated values of water content.

4) Results were expressed in approximate mass percentages arrived at by dividing the volume of water in the trap

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[4] 1944 Book of A.S.T.M. Standards, Part III, pp. 293 - 296, American Society for Testing Materials, 1945.

[5] Toluene boils at 110.6°C while fractions of petroleum naphtha boil as high as 210°C.

FIGURE 1

Heat Source Calibration Curve

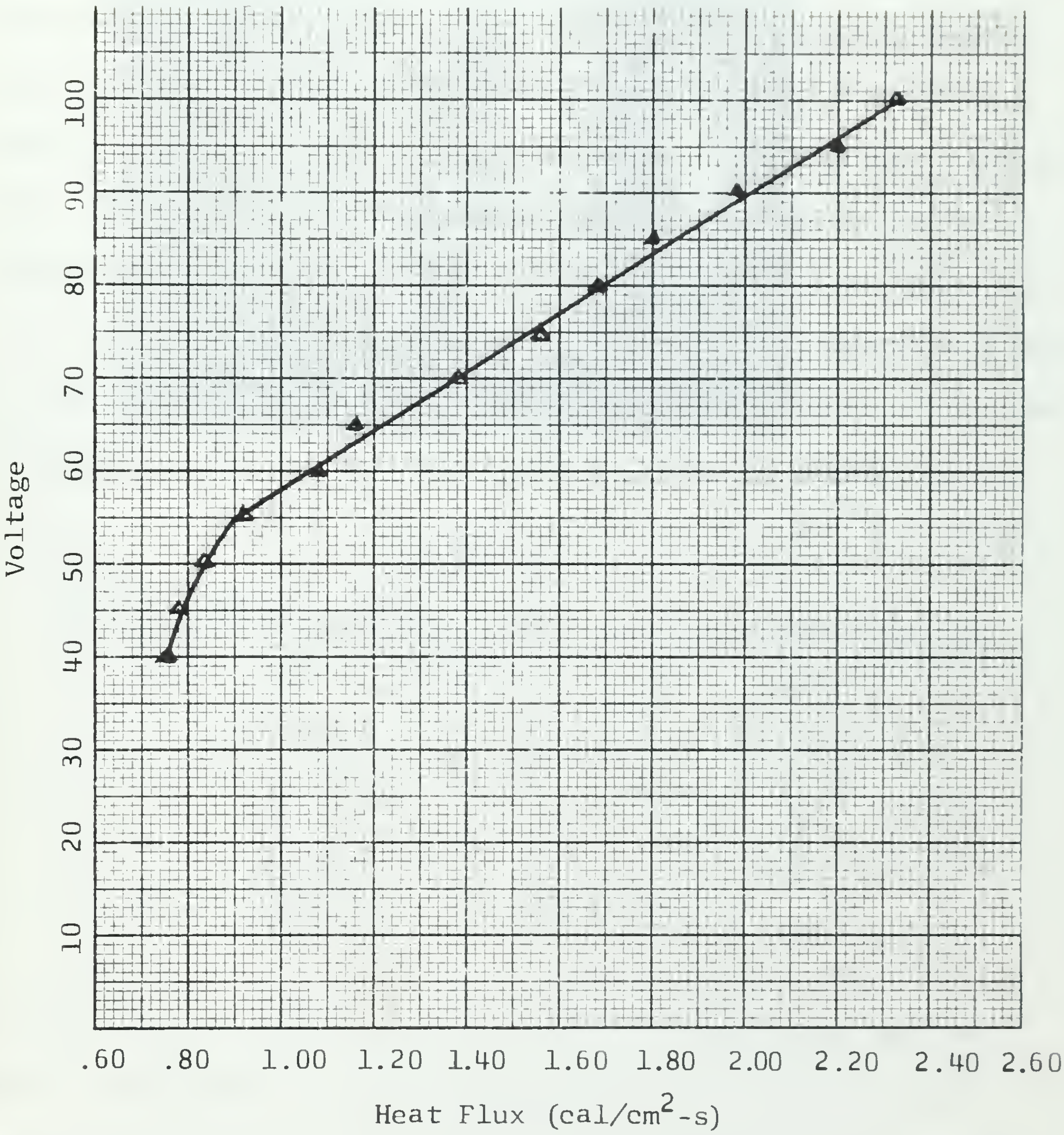


FIGURE 2

ASTM Water Content Determination Apparatus

by the weight of the crushed sample and multiplying the result by 100.

Due to the 10 ml capacity of the water trap, the size of the sample was determined by the anticipated water content of a specific test panel. The drier the wood, the larger the sample that was required to obtain an accurate water content analysis. With extremely wet wood, the problem was found to be that of choosing a small enough sample to avoid overloading the calibrated trap. When that happened, no satisfactory method was found to salvage the test, with the result being the concurrent ignition test of the parent panel was rendered worthless. The best results were obtained using the empirical criteria for sample size versus anticipated water content set forth in Table II below.

TABLE II

Anticipated Water Content (%)	Optimum Sample Size (g)
0-5	100
5-10	60
10-20	40
20-30	30
30-40	20

Extreme care had to be taken with test specimens and their parent test panels to avoid changes in water content during handling and testing. Disposable plastic surgeon gloves were worn while handling the wood to avoid moisture contamination from human perspiration. Edge samples of greater than required size were trimmed from the parent panel with a hatchet. The parent panel was replaced in its controlled environment while the water test specimen was being processed. A mechanical shredder was found to be very useful in shredding the test specimen to a proper size to pass easily through the neck of the distillation flask. The shredded specimens were weighed in tare-weighed plastic beakers and transferred quantitatively into the distillation flask by means of a large funnel. The apparatus was sealed immediately and the reflux distillation commenced.

For most consistent results, it was found that the ignition test should be run on the parent panel during the approximately two hours necessary for the water test specimen to distill its water content to a constant volume in the trap arm. The best readings of the water trap calibrations were after several hours of standing when the turbidity disappeared.

III. EXPERIMENTAL METHODS

A. CONDITIONING OF TEST PANELS

Selected panels of ponderosa pine cut to final dimensions of 12" x 18" x ½" were stored for a period of one year in a controlled environment room. The temperature was maintained at approximately 20°C at a relative humidity of approximately 50%. These panels stabilized at an average water content of 7.0 - 8.0% and served as control specimens and as a general starting point for conditioning to other water contents.

Some of these control panels were stored in a locker maintained at 100% relative humidity for varying periods of time to achieve test panels of increased water content. It was found that the gain in water content was very roughly about one percent per day of storage.

To produce panels of lowered water content, moderate heating in a vacuum oven for periods of two to ten days produced the best results. Temperatures were normally maintained in the range of 60 - 80°C at a vacuum of approximately 20 inches of mercury. Prior to the use of the vacuum oven, several attempts to produce low water content panels by oven drying at temperatures over 100°C produced panels with areas of light to moderate charring which were unsatisfactory for test use.

In order to render surface characteristics of the test panels as uniform as possible, all panels were wiped down with fine garnet paper prior to ignition testing. Panels which had been subjected to heating were lightly sanded to remove any surface discolorations at the time they were removed from their storage environment for a specimen to be taken for water content analysis.

All test panels were restored to their respective storage environments after the water content sample was taken and were removed only when ignition testing of a specific panel was to be immediately undertaken.

Most consistent results were achieved when all work on a given test panel was accomplished in the shortest possible time after its initial removal from environmental storage. With practice, this total elapsed time was found to be approximately two hours.

B. IGNITION TESTING PROCEDURES AND COLLECTION OF DATA.

It was observed in a series of empirical tests using control test panels that unpiloted ignition did not occur uniformly over the surface of a specific test panel at any single minimum value of incident heat flux. The range of heat flux required to produce unpiloted ignition varied from approximately 1.2 to 2.6 cal/cm^2-s. As a result of this observed non-uniformity of response, it was decided to develop a statistical technique that would make use of this very non-uniformity to yield useful data.

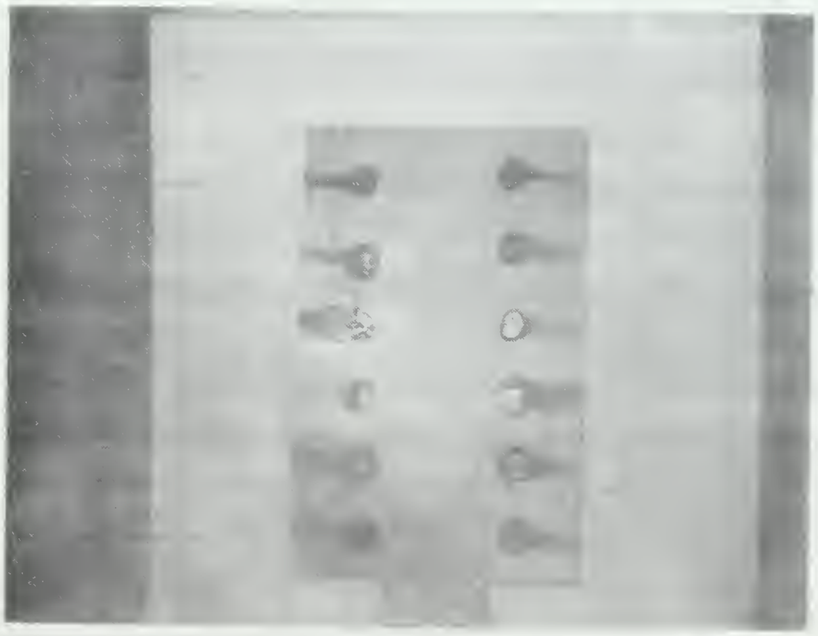
The problem was found to be similar to that encountered in the explosives field in which impact sensitivities of a single explosive or explosive mixture may vary widely over a range of impact energies. Sinclair [2] resolves this problem by utilizing a statistical approach that takes into account the full range of apparent sensitivities and uses it to generate a fifty percent point of probable impact detonation which in itself forms a useful item of information as well as being the

FIGURE 3

Ignition Test Apparatus

FIGURE 4

Test Panel After Irradiation



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Impact Test Data Sheet

FIGURE 5

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	X Ratio	%	Remarks
150																												
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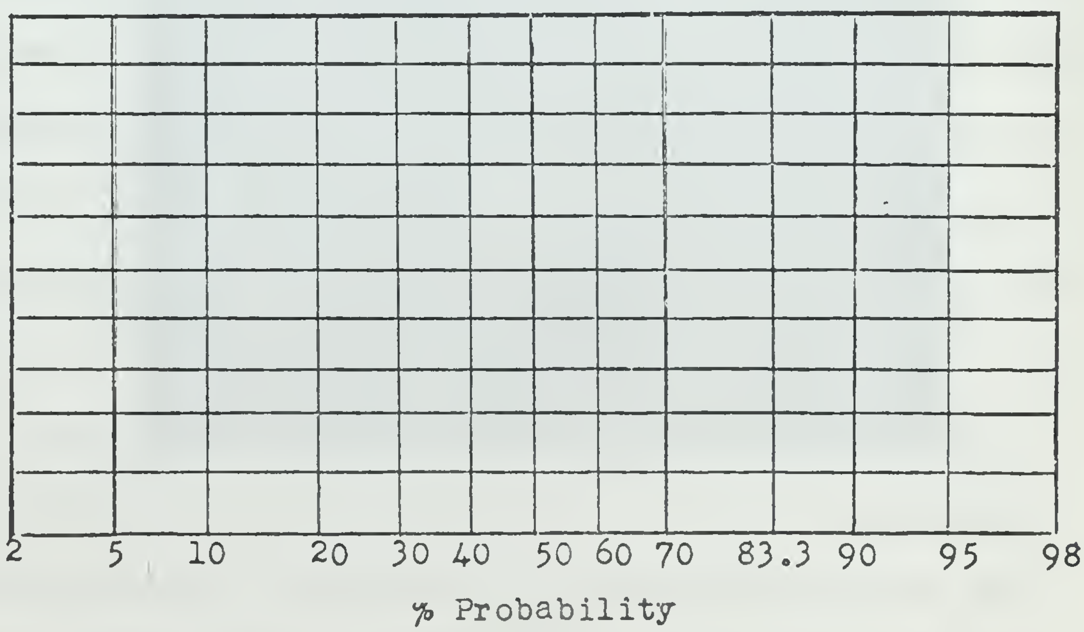

basis for a comparison of sensitivities. As a result, a similar approach was used with unpiloted ignition wherein equidistantly spaced discrete values of incident heat flux were used in place of impact drop heights as is the case with explosives.

In the following paragraphs, the arbitrary but consistent assumptions and procedures followed throughout the testing are stated.

All test panels were aligned in a holding vice at the standard standoff distance from the heat source. A row of six approximately equally spaced areas was irradiated along the top and bottom of both the back and front of each panel for a total of 24 ignition test points per panel. See Figures 3 and 4 for illustrations of the apparatus and a sample test panel, respectively.

The range of incident heat flux found to be of significance possessed a linear correlation with input voltage to the heat source. Therefore, all ignition data were recorded in terms of voltage input in discrete five volt intervals corresponding to heat flux intervals of approximately 0.15 cal/cm^2-s. In the event that the heat source calibration curve had not proved linear with voltage, then the data would have been scaled in less regular voltage intervals or in their heat flux equivalents in such a manner to produce equally stepped heat flux intervals. In this case, the linearity was merely convenient but not necessary in that it permitted use of the Impact Test Data Sheet with only the minor change of noting that voltage inputs not drop height were being used. See Figure 5 for blank data recording sheet.

All data points are considered on a strict "go - no go" basis. While the time required to produce ignition varied with each level of flux intensity as well as with the moisture content of the wood, it was found that if ignition had not occurred within 35 to 40 seconds, with 15 to 30 seconds being the average time frame, it would not occur at all. This was true even when irradiation was continued for a sufficient time to char completely through the test panel. No exceptions were observed in over 500 ignition tests. As a result, the arbitrary time of 120 seconds was allowed for ignition to occur in the form of a visible flame. If no flame was produced within the allowed time, it was held that ignition had not occurred and the test point on the data sheet marked with an "N." If a flame occurred with the allowed time, the data sheet was marked with a "B." See Figure 6 for an example of recorded data points.

As explained by Sinclair [2] approximately 20 to 25 data points were required to give an adequate statistical sample. Since there were only about 24 test areas per unique test panel, it was essential to start the testing at a proper level of flux intensity to generate an adequate number of data points. Previous empirical testing had established a range of requisite heat source voltage inputs ranging from 55 to 100 volts as the levels required to produce ignition in control test panels. As a result, the high median point of the range, taken as 80 volts, was used as a starting point for most test panels. If the number of test sites to a given specimen is limited as it was in this case, establishment of a practical test range in order to establish a reasonable starting point is deemed to be worthwhile. It was found to be an easy matter to modify the initial starting point if a particular trend in the variable being examined was established.

The results obtained at any one data point determined what would be done at the next succeeding data point. For example, if an input of 80 volts produced ignition, the next input would be stepped downward to 75 volts. If, however, no ignition had taken place at 80 volts, then the next input would have been stepped upwards to 85 volts. If a given point was successful, the next trial was stepped downward. If it was unsuccessful, the next trial was stepped upward. This pattern was continued until all areas on a given test panel were tested.

IV. PROCESSING OF TEST DATA

Figure 6 shows a completed test data sheet from an actual test. The ratio of successful ignition points to total trials were counted and equivalent percentages computed for each voltage input level. The percentage of successful ignition against the respective input voltage is plotted on the blank probability graph sheet provided on the lower portion of the data sheet. As can be seen in Figure 6, for the purpose of picking a point of 50% probability of ignition, the results were less than satisfactory.

However, by applying an innovation introduced by Sinclair, the situation shown in Figure 6 was improved considerably. The basic problem was an insufficient number of data points at each trial level. Since only a limited number of data points were available from each test panel, further testing was out of the question. To generate further data points without further testing the following assumptions were made:

1) If at any given data point, ignition occurred, it would have also occurred at all higher trial levels at that point.

2) If at any given data point, ignition failed to occur, it would have also failed to occur at all lower trial levels at that point.

Working with these two assumptions, it was possible to generate a family of pseudo-data points which were considered to be as valid as the actual data points. Figure 7 shows the same test depicted in Figure 6 with pseudo-data points added and

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FIGURE 6

Impact Test Data Sheet

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	X Ratio	%	Remarks
150																												
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125																												
120																												
115																												
110																												
105																												
100																												
95																												
90			B				B																			2/2	100	
85		N		B		N		B												B						3/5	60	
80	N				N				B		B		B						N		B		B			5/8	62	
75										N		N		B		B		N				N		B		3/7	43	
70															N		N								B	1/3	33	
65																										0	0	
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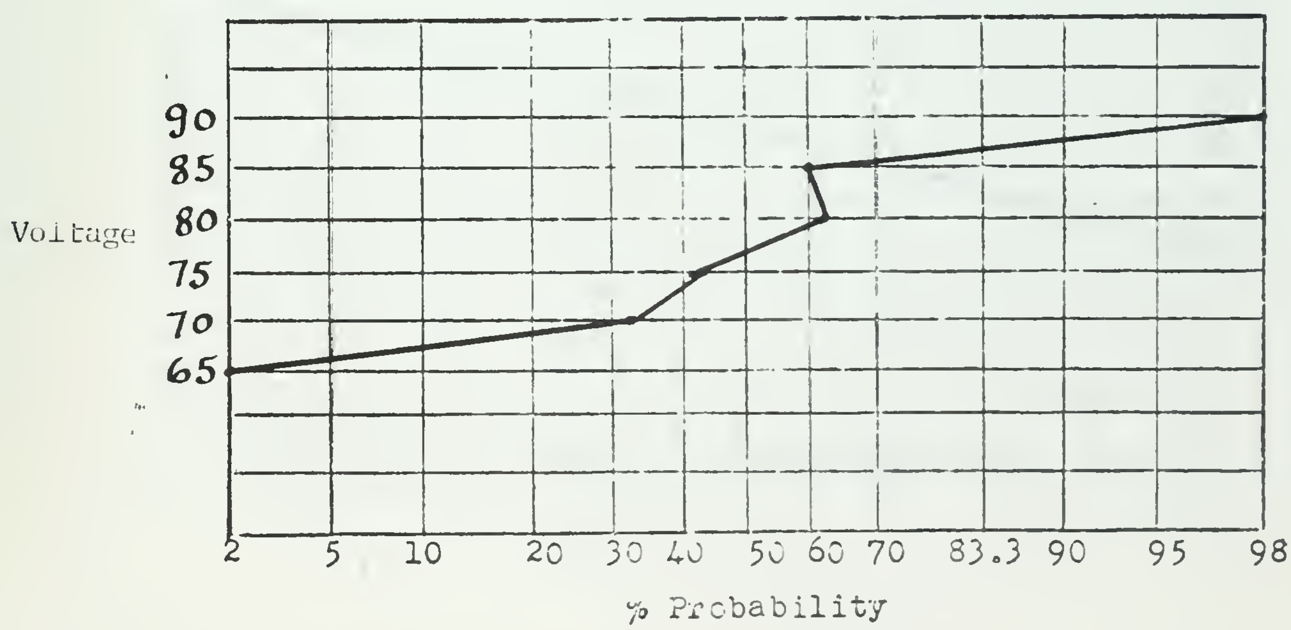

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Impact Test Data Sheet

FIGURE 7

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	X Ratio	%	Remarks
150																												
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120																												
115																												
110																												
105																												
100																												
95																												
90			B	B			B	B	B		B		B	B		B				B	B		B	B	B	14/14	100	
85		N		B		N		B	B		B		B	B		B				B	B		B	B	B	12/14	86	
80	N	N			N	N			B		B		B	B		B			N		B		B	B	B	9/14	64	
75	N	N			N	N				N		N		B		B		N	N			N		B	B	4/13	31	
70	N	N			N	N				N		N			N		N	N	N			N			B	1/12	8	
65	N	N			N	N				N		N			N		N	N	N			N				0/10	0	
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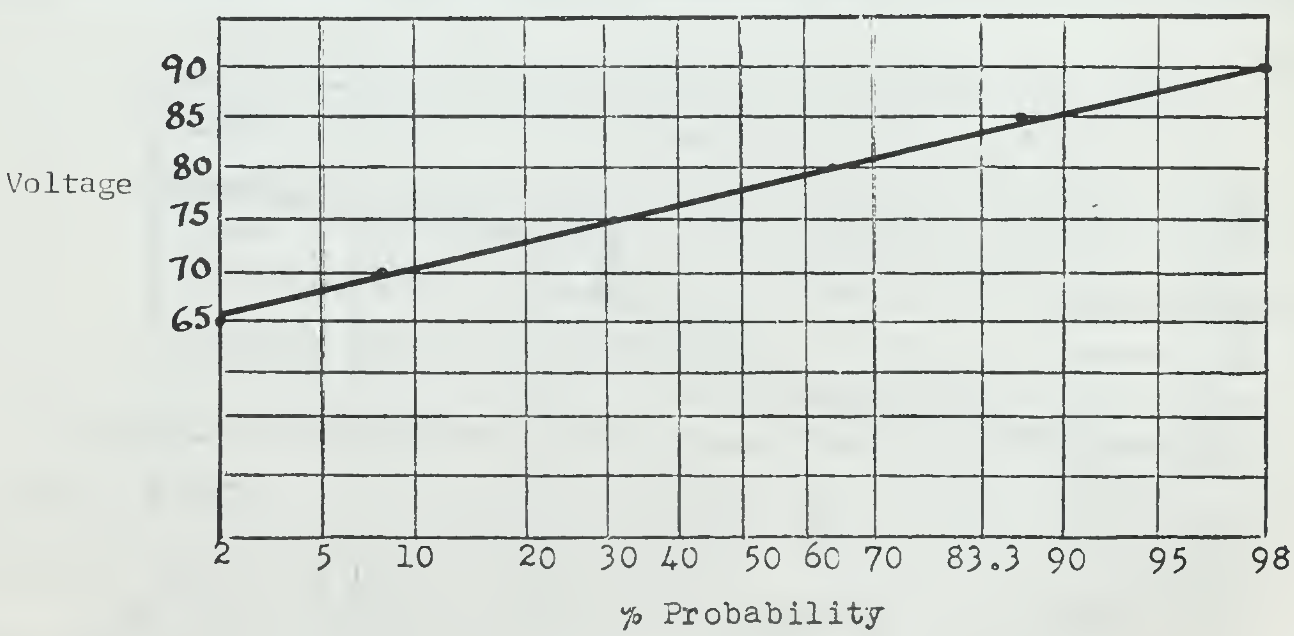


considered in the counting, computation, and plotting of percentage successes at all trial levels. The linear relationship between the probability points made selection of an input equivalent to 78 volts as the 50% probability point an easy matter.

V. EXPERIMENTAL RESULTS

Using the apparatus and methods previously described in this paper, unpiloted ignition testing was conducted on test panels of differing water contents. All water contents are expressed in mass percentages. The results of the testing are given numerically in Table III and presented graphically in Figures 8, 9, and 10.

In Table III, the results obtained for each level of water content are presented in terms of both input voltage and the equivalent heat flux for the following points:

1) Minimum point - the lowest heat flux at which ignition occurred on the specific test panel.
2) 50% point - the statistically derived heat flux at which ignition would be expected 50% of the time.
3) 100% point - the lowest level of heat flux where ignition occurred 100% of the time.

Figures 8, 9, and 10 provide respectively graphical representation of the minimum, 50%, and 100% points observed or derived as plotted against test panel water content percentages.

Figure 11 is a smooth summary of the individual graphical presentations shown in Figures 8, 9, and 10.

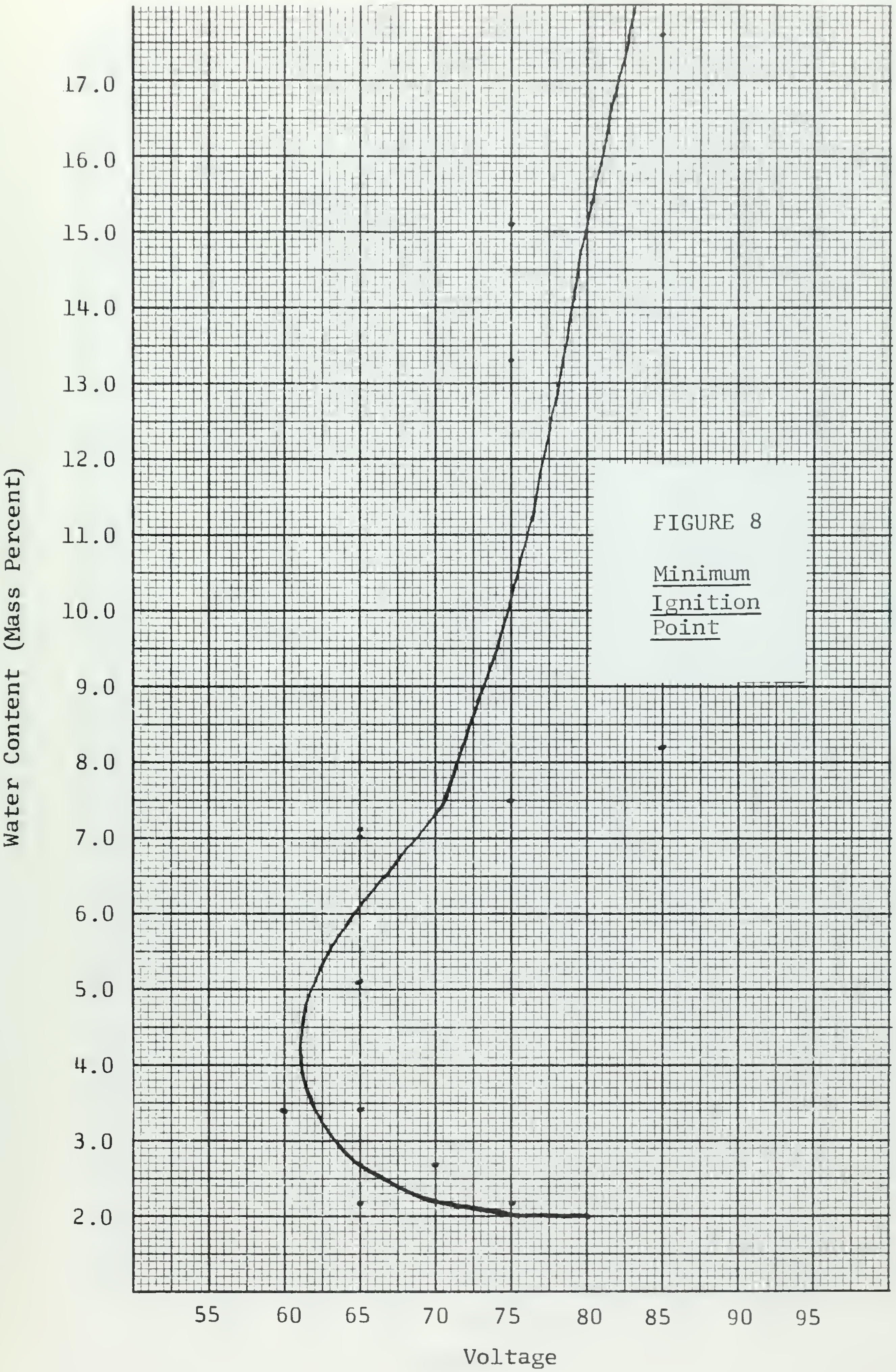
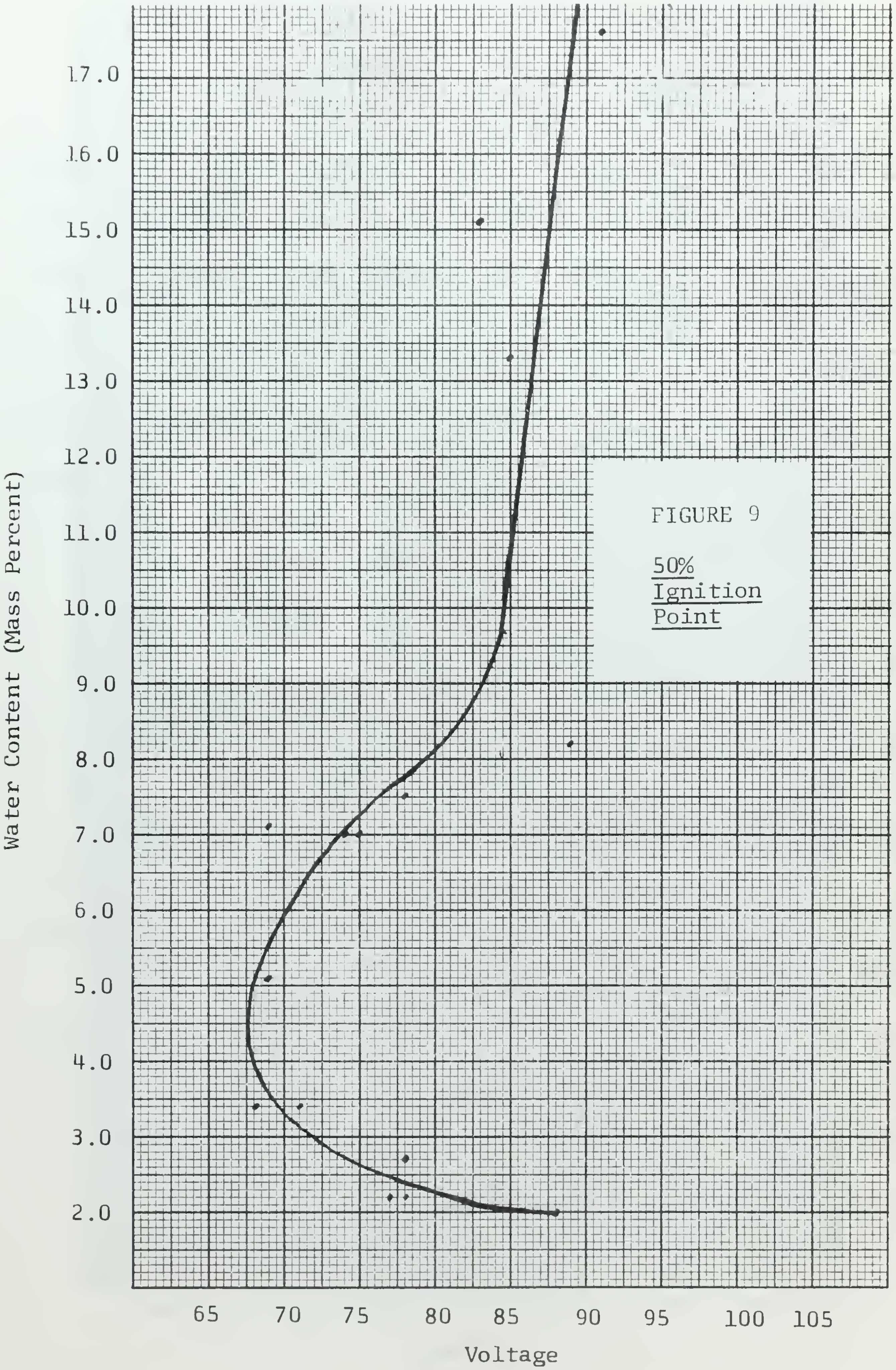
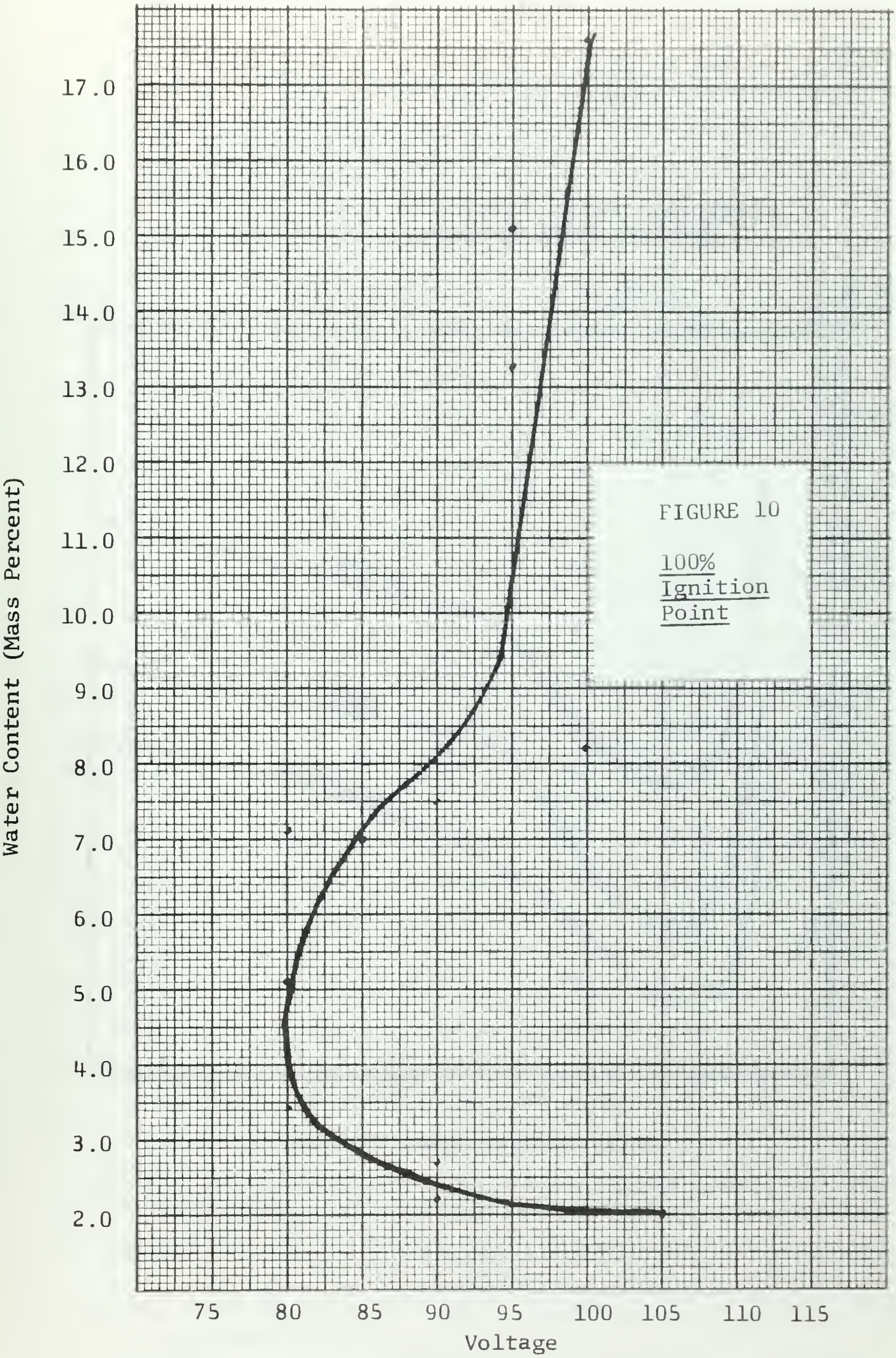


FIGURE 8

Minimum Ignition Point


Water Content (Mass Percent)
17.0
16.0
15.0
14.0
13.0
12.0
11.0
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
65
70
75
80
85
90
95
100
105
Voltage
FIGURE 9
50%
Ignition
Point



Water Content (Mass Percent)
17.0
16.0
15.0
14.0
13.0
12.0
11.0
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
75
80
85
90
95
100
105
110
115
Voltage
FIGURE 10
100%
Ignition
Point

FIGURE 11

Summarized Smooth Results of
Ignition Point Curves

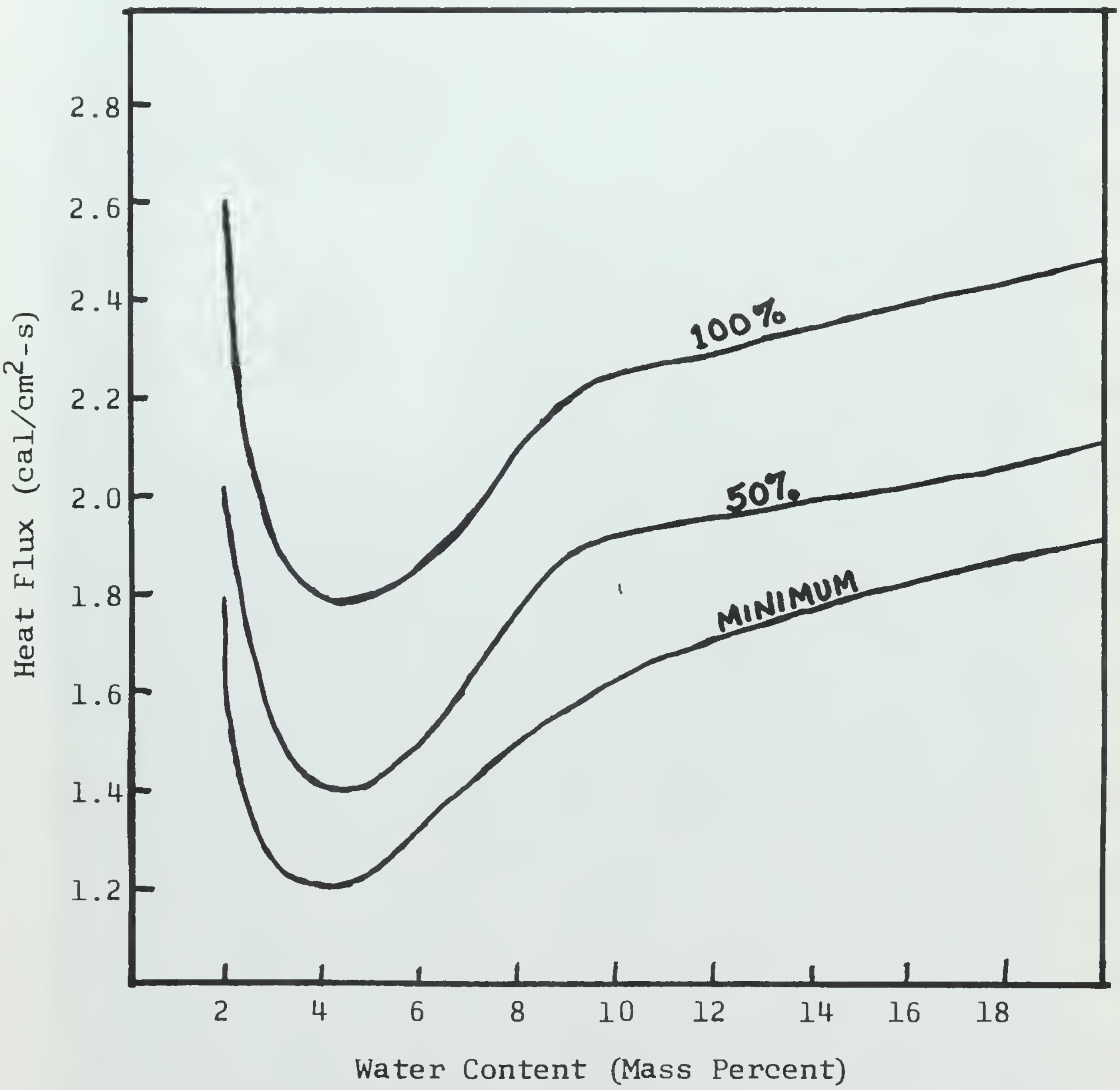


TABLE III[6]

Water Content	Minimum Point Input	Minimum Point Flux	50% Point Input	50% Point Flux	100% Point Input	100% Point Flux
2.0	80	1.79	88	2.03	105	2.59
2.2	65	1.32	77	1.69	90	2.11
2.2	75	1.63	78	1.73	90	2.11
2.7	70	1.47	78	1.73	90	2.11
3.4	60	1.16	71	1.51	80	1.79
3.4	65	1.32	68	1.41	80	1.79
5.1	65	1.32	69	1.44	80	1.79
7.0	65	1.32	74	1.60	85	1.95
7.0	65	1.32	75	1.63	85	1.95
7.1	65	1.32	69	1.44	80	1.79
7.5	75	1.63	78	1.73	90	2.11
8.2	85	1.95	89	2.08	100	2.42
13.3	75	1.63	85	1.95	95	2.27
15.1	75	1.63	83	1.89	95	2.27
17.6	85	1.95	91	2.14	100	2.42

[6] All water content units are in mass percentages, all inputs are voltages, and all flux units are cal/cm^2-s.

VI. DISCUSSION

The results of this study of unpiloted ignition of planar surface ponderosa pine as set forth in Section V, but most explicitly in Figure 9, indicated that the highest probability of unpiloted ignition occurred not at the lowest water content but in a range of approximately 3% to 6% water content.

Proceeding from higher water contents down to the intermediate range where the minimum occurs, the overall trend was not surprising. It was reasonable to expect wood of lower water content to ignite more readily than wood of higher water content. The appearance of a minimum before the lowest water content values were reached, requiring an increase in heat flux to produce ignition as water content approached the lowest values attainable in the experiment, was not in accordance with prior expectations and appeared to be anomalous behavior.

Simms and Law [3] have studied the effect of moisture content on the unpiloted ignition of pine. Their conclusions are compatible with the results obtained in the present series of experiments insofar as the higher moisture content portions are concerned. However, no anomalous region is reported due to the fact that they tested no specimens of such extremely low moisture content as were used to obtain the data in this particular region. In concluding that increased water content necessitated increased flux densities for unpiloted ignition, the reasons for this effect were summarized as follows:

1) Increased water content increased both the thermal conductivity and the specific heat of the wood allowing increased cooling inward of the irradiated surface.

2) Heat is transferred directly by the molecular diffusion of the water. The more water, the greater is the diffusion of heat.

3) Evaporation cools the hotter regions and condensation heats the cooler regions.

4) Water vapor in the atmosphere or in the volatile outgassing products is an inerting gas toward ignition processes.

It is believed that the reasoning set forth by Simms and Law is substantially correct in their first three conclusions. This should have lead to a more rapid local heating at the irradiated surface with rapid charring and pyrolysis. This was observed to be the case at the lowest water contents. In spite of this, ignition was more difficult at these lowest water content levels.

The fourth conclusion concerning the exclusively inerting function of water vapor is deemed worthy of further study. It is possible that only above certain minimum levels water vapor acts as an inerting gas. Hawley[7] states that the yield of water from the destructive distillation of wood varies between 22.3% to 27.8% exclusive of the naturally occurring water as such within the wood. Since water vapor will be normally present in the

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[7]Hawley in Wood Chemistry, ed. by L. E. Wise, ACS Monograph Series No. 97, p. 686, Reinhold, 1946.

outgassing products in at least a 25% to 35% fraction, it is certainly possible that unless a certain water vapor proportion is maintained, the ignition reaction is forced to other higher energy pathways.

Norrish [4] discovered that the hydroxyl radical is intimately associated as an initiator with many very fast chemical reactions such as ignition, combustion, and explosions. The function of water vapor in a mixture of combustible volatiles and air such as is found in the potentially ignitable outgassing from thermally and photochemically irradiated wood is not known, but certainly merits consideration.

There is certainly a possibility that water, physically entrapped in the complex polymers that constitute wood may enter either physically or chemically or both in the complex pyrolytic decomposition processes caused by thermal irradiation. Below certain levels of entrapped water content, pyrolysis may proceed either in more energy consuming pathways or may produce decomposition products less susceptible to ignition.

It was observed that if ignition failed to occur, a flameless combustion similar to that of burning charcoal often occurred. The fact that this process appeared to occur more readily at lower water contents is not incompatible with the strongly localized heating caused by lack of heat transfer attributable to low water content. If a burning charcoal surface occurs, this surface might compete favorably with flame combustion for pyrolysis products including water, to such an extent that the conditions for flame ignition might not occur.

However, without additional research any one or combination of these explanations cannot be considered as either correct or incorrect. It is the hope of this writer, that the primary purpose of this research has been realized in setting forth the apparatus and methods whereby the relative susceptibility of various substances or a given substance over the range of a variable factor to unpiloted ignition by thermal radiation may be determined with a reasonable degree of reproducibility.

While it was interesting to speculate on the probable causes of the anomalous region reported, a full explanation of this phenomenon was not held to be either within the scope or intent of this research.

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13. ABSTRACT

The unpiloted ignition of wood caused by thermal radiation varies widely when only small areas of the test panel are irradiated. In order to make a comparison of the effect of a given variable, which in this case was water content, a statistical method was devised which yielded a 50% probability of ignition point as a standard of comparison. The results of the testing were predictable at higher water contents in which the requisite heat flux to produce ignition was an increasing function of increasing water content. At extremely low water content an unexpected increase in the requisite heat flux required for ignition was observed. While several explanations are possible to account for the observed anomaly, selection of any one exclusive explanation was not made due to the lack of sufficient data.

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